Millimeter-wave fixed-tuned subharmonic mixers with planar Schottky diodes

Yao Changfei(姚常飞)[1,2,†], Zhou Ming(周明)[2], Luo Yunsheng(罗运生)[2], Wang Yigang(王毅刚)[2], and Xu Conghai(许从海)[2]

[1]Science and Technology on Monolithic Integrated Circuits and Modules Laboratory, Nanjing Electronic Devices Institute, Nanjing 210016, China
[2]Department of Microwave and Millimeter Wave Modules, Nanjing Electronic Devices Institute, Nanjing 210016, China

Abstract: Two different frequency bandwidth subharmonic mixers (SHM) using planar Schottky mixing diodes are discussed and fabricated. Full-wave analysis is carried out to find the optimum diode embedding impedances with a lumped port for modeling the nonlinear junction. The SHM circuit is divided into several different parts and each part is optimized using the calculated diode impedances. The divided parts are then combined and optimized together. The exported S-parameter files of the global circuit are used for conversion loss (CL) discussion. For the 150 GHz SHM, the lowest measured CL is 10.7 dB at 153 GHz, and typical CL is 12.5 dB in the frequency range of 135–165 GHz. The lowest measured CL of the 180 GHz SHM is 5.8 dB at 240 GHz, and typical CL is 13.5 dB and 11.5 dB in the frequency range of 165–200 GHz and 210–240 GHz, respectively.

Key words: millimeter wave; planar Schottky diodes; subharmonic mixer; conversion losses
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1. Introduction

Millimeter- and sub-millimeter-wave techniques are widely applied for radio astronomy, molecular spectroscopy, atmospheric remote sensing, scaled radar range systems, monitoring of chemical and biological molecules, increased security for point-to-point communications, as well as covert battlefield communication systems. Until now, commercial low noise amplifiers are generally used at frequencies below 100 GHz, at higher frequencies, low noise amplifiers is unavailable. Therefore, the only solution to improve the sensitivity of millimeter- and sub-millimeter-wave receivers is to design high quality mixers, and a second harmonic mixer is commonly used in receivers as the first stage. The well developed SHM usually has low CL as fundamental mixers, and it presents high local oscillator (LO) signal rejection and requires low pump LO frequencies. The preferred non-linear device for room temperature mixers is the Schottky diode. This device also operates well in harmonic multipliers and outperforms solid-state oscillation frequency sources above 100 GHz. Millimeter- and sub-millimeter-wave mixing and multiplying based on GaAs Schottky diode technology has reached an impressive level of maturity now[1−12].

In this paper, two different frequency bandwidth hybrid integrated SHMs with GaAs Schottky antiparallel diode pairs are developed. The circuit design methodology uses a combination of linear and nonlinear circuit simulations (ADS) to optimize and compute the performance of the SHM circuit, and 3D-EM simulations (HFSS) is applied to accurately model the diodes and waveguide structures. Different parts of the SHM circuit, including the diode cell, microstrip lines, waveguide transitions, and matching networks, are optimized together for the lowest CL in the required frequency range. For the 150 GHz SHM, the lowest measured CL is 10.7 dB at 153 GHz, and typical CL is 12.5 dB in 135–165 GHz. The lowest measured CL of 180 GHz SHM is 5.8 dB at 240 GHz, and typical CL is 13.5 dB and 11.5 dB in 165–200 GHz and 210–240 GHz, respectively.

2. Circuit design

An iterative "divide and combine" design approach is adopted, breaking up the SHM circuit into different parts, where each part is simulated and optimized individually. The different parts are then combined and optimized together. The design process of the SHM circuit is presented in Fig. 1.

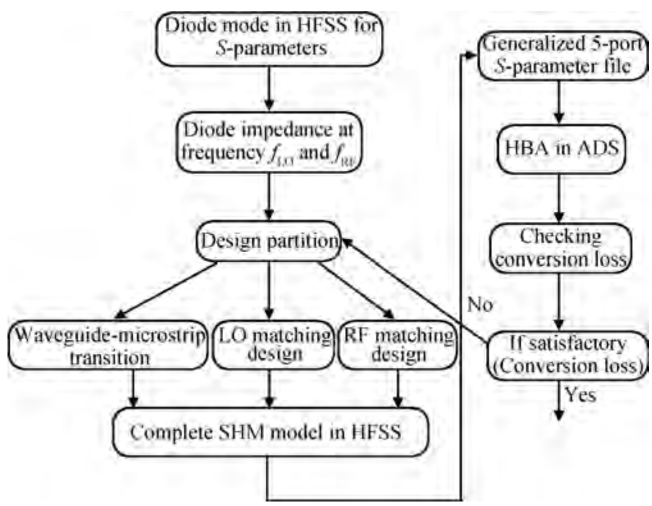

Fig. 1. SHM design process flow chart.

† Corresponding author. Email: yaocf1982@163.com
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Table 1. Diode material parameter values in HFSS.

N^{++} GaAs epitaxial	Perfect conductor
N GaAs buffer layer ($\varepsilon_r = 12.9$) GaAs substrate ($\varepsilon_r = 12.9$) SiO_2 layer ($\varepsilon_r = 4$)	Lossless dielectrics

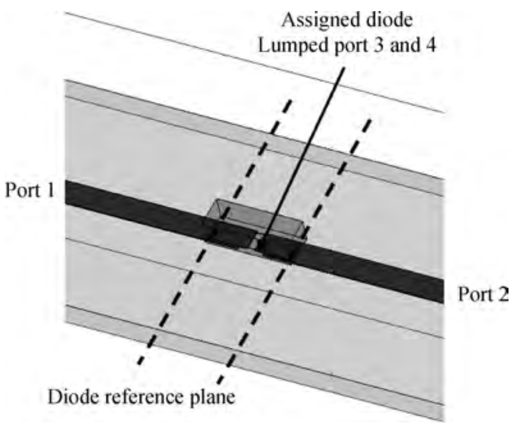

Fig. 2. Diode chip model in HFSS.

2.1. Diode model embedding impedances

A flip chip planar Schottky antiparallel mixing diode pair (type TSC-AP-03020 from Teledyne Scientific Company) is applied for SHM[13]. When the operation frequency is high, the dimensions of the diode are $0.355 \times 0.13 \times 0.088$ mm^3 (length, width, and thickness, respectively), which can be comparable with operation wavelength. Accurate modeling of the diode chip is a fundamental task for the SHM design. In order to extract accurate characteristic parameters of the physical geometry and predict the diode chip optimum embedding impedances, HFSS software is adopted to extract the S-parameters of the passive structure. A full 3D-EM simulation of the diode chip in its circuit environment is analyzed to find the optimum embedding impedances. The material parameter values used during diode chip structural modeling are depicted in Table 1. The 3D-EM simulation of the diode chip with an internal coaxial or lumped port is used at the Schottky diode junction. The diode non-linear part and passive circuit part is combined. The diode pad interface has been extruded and the transmission line ports are later de-embedded back to the diode reference planes, as described in Fig. 2. It is an essential operation that enables precise modeling. In fact, if the ports are too close to discontinuities they can interfere with the near field around these discontinuities and therefore effect calculations. The S-parameter file of the diode chip is exported for a diode model embedding the impedance discussion in ADS. The nonlinear Schottky junction diode model is modeled by SPICE parameters ($C_{jo} = 9.8$ fF, $I_s = 1.0 \times 10^{-14}$ A, $R_s = 5\ \Omega$, $n = 1.15$), which are entered into the diode model in ADS to simulate the diode nonlinear characteristic. The main SPICE parameters such as series resistance R_s, ideality factor n, saturation current I_s, are extracted by measuring the I–V curve, and zero bias voltage junction capacitance can be calculated by an identity[14]. The ideal diode component is connected to the internal port and down to ground. By running harmonic balance simulations, the diode optimum LO frequency, radio frequency (RF), and immediate frequency (IF) impedance is found. The values of impedance will be used to synthesize the real SHM.

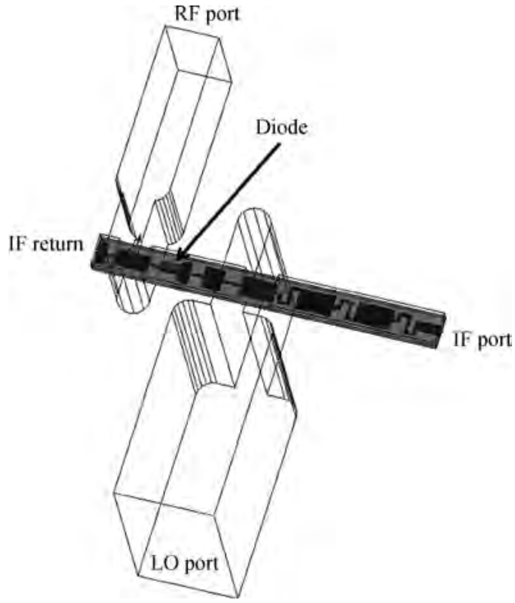

Fig. 3. Schematic of the SHM circuit.

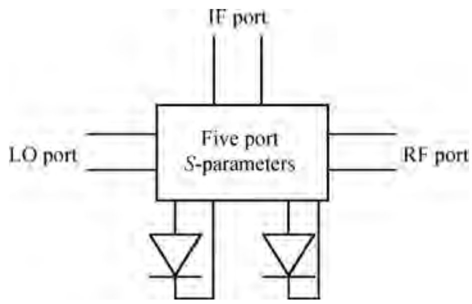

Fig. 4. Global optimization of the SHM.

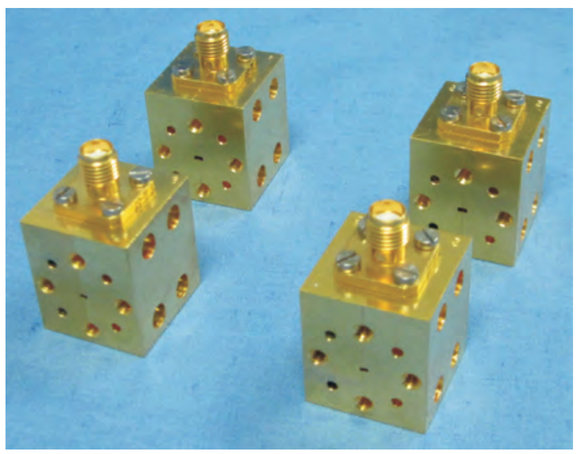

Fig. 5. Photo of the 150 GHz and 180 GHz SHM.

2.2. SHM circuit optimization

The SHM circuit structure is shown in Fig. 3. The quartz microstrip circuit consists of a grounded probe in the RF wave-

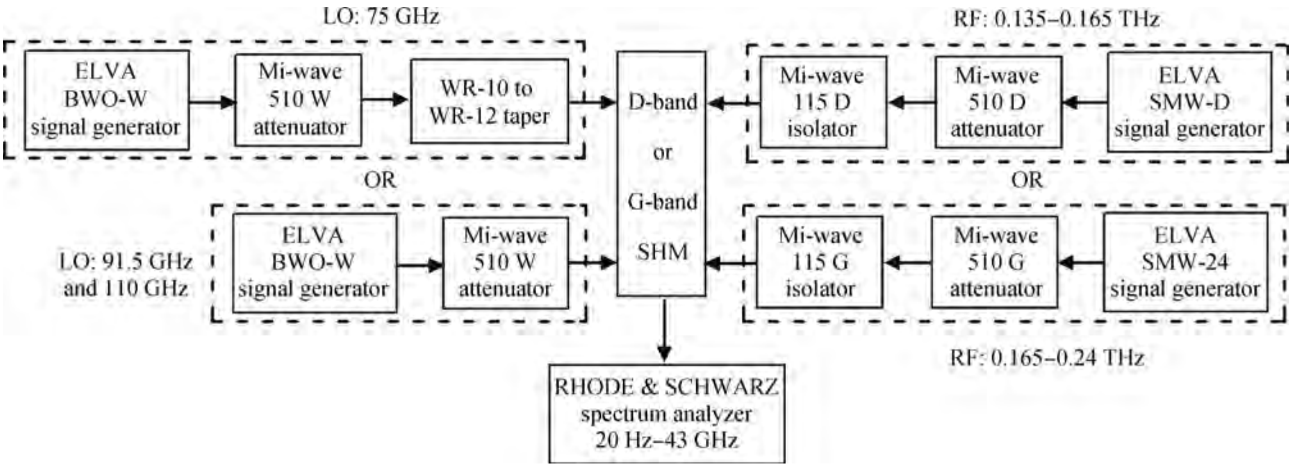

Fig. 6. Measurement setup of the 150 GHz and 180 GHz SHM.

guide by feeding microstrip transmission lines. The antiparallel diode pair is in series with the transmission line, a probe crossing the LO waveguide, and a low-pass IF filter (LPF) blocking the RF and LO signals. The circuit is IF-grounded at one end by contacting the RF waveguide wall, and the other end is the IF port with impedance of 50 Ω. All independent parts of the SHM (waveguide to microstrip transition, diode pair, LPF) are constructed and simulated respectively using HFSS. The calculated S parameters data of each part is exported for global optimization in ADS, a certain number of elements are optimized in a nonlinear simulator, such as the position of the waveguide backshort, and the length and height of the reduced waveguide (reduced waveguide height can provide broadband width and additional tuning functionality, but it is difficult to fabricate as it require large ratio of cutting tolls) and a certain number of high and low impedance matching lines. When the SHM CL response is optimized, all independent subcircuits are combined with a single HFSS model that can fully represent the real 3D SHM at as many harmonics as is necessary and resimulated to confirm that it behaved as expected. The multiport S-parameters of this simulation are extracted and then combined with the nonlinear mixing diode to model the conversion loss in ADS, as shown in Fig. 4. This process can be repeated for further complete optimization of SHM as described in Fig. 1.

3. Experimental results

The SHM split block is manufactured with brass and electroplated with gold. The SHM circuit substrate is ultra thin quartz substrates with a dielectric constant of 3.78 and thickness of 80 μm. To maximize repeatability of the SHM circuit, using available circuit fabrication processes and for the substrate to withstand stress due to large ratio of circuit length and width, the circuit size and reliability must be considered in the circuit design. Finally, the developed 150 GHz and 180 GHz quartz circuit size is 5.7 $\times$ 0.5 mm^2 and 4.95 $\times$ 0.4 mm^2, respectively. The circuit is mounted to the lower half of the split-waveguide block with silver epoxy (type H20E from Epotek). The antiparallel diode is glued to the circuit as in Fig. 3 with silver epoxy. The block photo is given in Fig. 5. The LO and RF port of the 150 GHz SHM are standard full-height WR-12 and WR-06 waveguides with waveguide dimensions of 3.1 $\times$ 1.55 mm^2 and 1.65 $\times$ 0.83 mm^2, respectively. The LO and RF port of the 180 GHz SHM are standard full-height WR-10 and WR-05 waveguides with waveguide dimensions of 2.54 $\times$ 1.27 mm^2 and 1.3 $\times$ 0.65 mm^2, respectively. A SMA is connected to the end of the IF microstrip port for IF signal output.

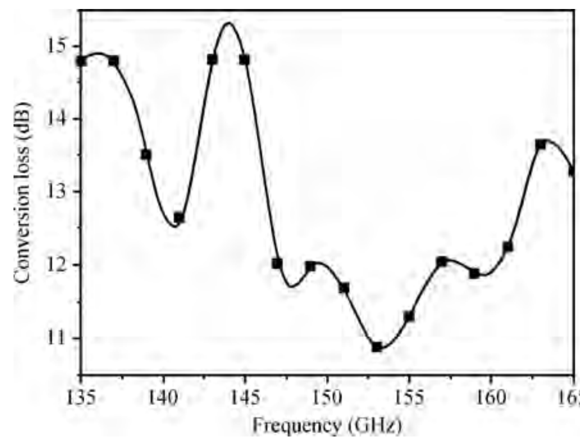

Fig. 7. Measured performance of the 150 GHz SHM with LO frequency at 75 GHz.

The SHM measurement setup is presented in Fig. 6. LO signals of the SHM are provided by an ELVA-1 BWO-W signal generator, and pump power is adjusted by using a Mi-Wave attenuator. The RF signals are provided by ELVA-1 BWO-D and ELVA-1 SMW-24 signal generators, and its output power to SHM is precisely calibrated by a millimeter and sub-millimeter power meter PM-4. Output IF signals are detected by using a Rhode & Schwarz spectrum analyzer. As presented in Fig. 7, to the 150 GHz SHM, the lowest measured CL is 10.7 dB at 153 GHz, and the typical CL is 12.5 dB in 135–165 GHz with pump power of 20 mW at 75 GHz. As shown in Figs. 8 and 9, the lowest measured CL of 180 GHz SHM is 5.8 dB at 240 GHz, and typical CL is 13.5 dB in 165–200 GHz with pump power of 10 mW at 91.5 GHz. Tested typical CL is 11.5 dB in 210–240 GHz with pump power of 10 mW at 110 GHz. The cutoff frequency of the RF port waveguide is higher than the LO signals, infinite isolation of LO-RF port can be realized in theory.

Table 2. Performance comparison of SHM.

Parameter	Model (D-band)	CL (dB)	Model (G-band)	CL (dB)	Test condition	Illustration
This paper	0.135–0.165 THz	Typ 12.5	0.165–0.2 THz	Typ 13.5	SSB	Single side band (SSB)
	0.147–0.153 THz	< 12	0.21–0.24 THz	Typ 11.5		CL is higher than
		Min 10.7		Min 5.8		double side band (DSB)
Ref. [1]	SPM-06	Typ 8.5	—	—	DSB	CL 3 dB in theory
Ref. [3]	WR6.5SHM	< 7.0	WR5.1SHM	< 7.0	DSB	
		Min 5.5		Min 6.0		
Ref. [8]	—	—	160–204 GHz	7–17	DSB	
Ref. [12]	140–170 GHz	< 13	—	—	DSB	

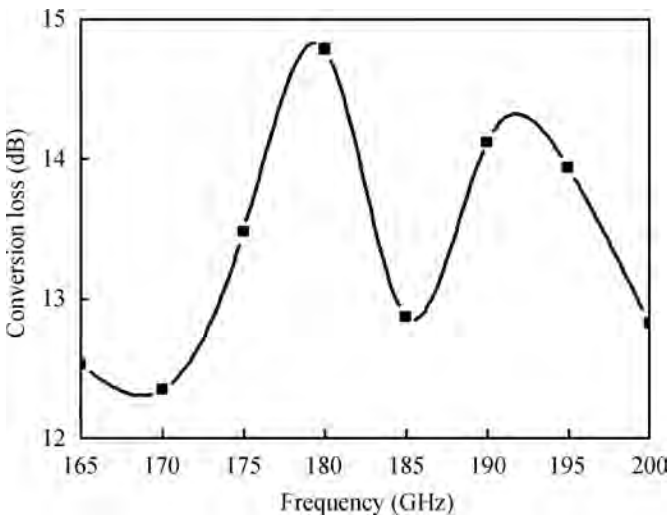

Fig. 8. Measured performance of the 180 GHz SHM with LO frequency at 91.5 GHz.

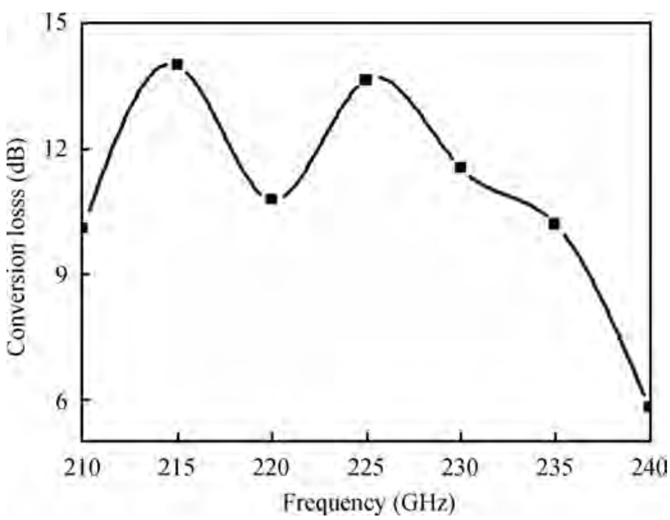

Fig. 9. Measured performance of the 180 GHz SHM with LO frequency at 110 GHz.

Table 2 illustrates commercial SHM product performance employing GaAs planar Schottky barrier mixing diodes. Obviously, the SHM typical measured CL is worse than VDI products by about 4 dB (VDI represents state-of-the-art performance in terahertz multiplying and mixing in word wide), and the lowest measured CL of the 180 GHz SHM is superior. This work plays a solid foundation for future work for even high frequency SHM.

4. Conclusions

Two different frequency band SHMs are analyzed and designed with planar Schottky barrier diodes. Full-wave analysis is carried out to find diode embedding impedances with a lumped port to model the nonlinear junction. An iterative "divide and combine" design approach is adopted, breaking up the circuit into different parts, where each part is simulated and optimized individually. The different parts are then combined and optimized together. The optimized exported S-parameters of the circuit are used for conversion loss analysis. To the 150 GHz SHM, the lowest measured CL is 10.7 dB at 153 GHz, and typical CL is 12.5 dB in 135–165 GHz with LO signal pump power of 13 dBm at 75 GHz. The lowest measured CL of 180 GHz SHM is 5.8 dB at 240 GHz, and typical CL is 13.5 dB and 11.5 dB in 165–200 GHz and 210–240 GHz with LO signals pump power of 10 dBm at 91.5 GHz and 110 GHz, respectively.

The SHMs are simple, compact, low cost, fixed-tuned, and low conversion loss, which is very attractive for millimeter and sub-millimeter wave test instruments, low noise receiver front-ends, and corresponding application systems.

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